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Subsidence of Organic Soils, Sacramento–San Joaquin Delta, California

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ABSTRACT

The Sacramento–San Joaquin Delta was reclaimed in the late 1800s when levees were built to convert this then tidal marshland into agricultural tracts and islands. Since then, land-surface elevations have declined, or subsided, by as much as 6 m. The spatial variability and causes of subsidence of organic soils in the Sacramento–San Joaquin Delta were evaluated by analyzing historical leveling data and changes in land-surface elevations relative to powerpole foundations. Analysis of the historical leveling data indicate that subsidence rates are slowing, and the spatial variability in subsidence rates was largely explained by differences in soil organic matter content.

The relation between land subsidence and organic matter oxidation was evaluated by measuring the gaseous and aqueous carbon flux and land-surface elevation changes in drained agricultural fields on three Delta islands. From July 1990 to May 1992, monthly gaseous CO_2 fluxes were measured. The CO_2 flux was used as an indicator of organic matter oxidation. Dissolved carbon fluxes were determined from the dissolved carbon loads in drainage ditches. Land-surface elevation changes were measured continuously by extensometers. The CO_2 flux was strongly affected by soil temperature and also was related to the thickness of organic soils and soil moisture. Land-surface elevation fluctuated elastically with changes in ground-water elevation. The net, rates of inelastic subsidence ranged from 0.46 to 1.06

cm/yr. Subsidence calculated from the CO_2 fluxes generally agreed with subsidence measured during the monitoring period and explained about 60–76 percent of the variance in inelastic changes in land-surface elevation measurements. Estimates of dissolved organic carbon flux for all three islands were small relative to gaseous CO_2 losses and represent less than 1 percent of the measured subsidence.

To evaluate the hypothesis that converting drained agricultural areas into wetlands could aid in subsidence mitigation by slowing the oxidation of the organic soils, carbon mass balances were determined on plots that were seasonally flooded, seasonally flooded and irrigated, and permanently flooded. Average fluxes were not significantly different between the irrigated and seasonally flooded plots. The carbon flux from the permanently flooded plot was about five times lower than the fluxes from the seasonally flooded and irrigated plots. Methane (CH_4) was the primary gaseous carbon species in the permanently flooded plot.

Carbon inputs were determined by harvesting and analyzing the accumulated vegetative biomass. There was a net carbon gain in the permanently flooded plot and a net carbon loss in the irrigated and seasonally flooded plots. The net carbon gain and the field observation of vegetative accretion in the permanently flooded plot indicate that permanent flooding may be a way to reverse the effects of subsidence in the delta.

INTRODUCTION

Prior to 1850, the Sacramento–San Joaquin Delta (fig. 1) was a tidal marsh. The delta was drained for agricultural use beginning in the late 1800s. The organic or peat deposits of the delta formed during the last 10,000 yr at the confluence of the Sacramento and San Joaquin Rivers from decaying plants. The drained organic soils on over 100 islands and tracts are highly valued for their agricultural productivity and have undergone continuous subsidence since drainage. The island surfaces of most of the delta islands are now 3 to 8 m below sea level and are protected from inundation by a network of levees. As subsidence continues, the potential for flooding due to levee failure increases significantly. Several levee failures in the past century were never repaired and have caused permanent flooding of the agricultural land (Hundley, 1992; Rojstaczer and Deverel, 1995).

Flooding in the region has statewide significance beyond the local damage because of the delta's critical location. The delta is the transfer point for the most of agricultural, municipal, and industrial water supplied to southern California. The system of levees and islands in the delta impedes the movement of brackish water landward and thereby usually allows transfer of relatively fresh water to the California Aqueduct (Hundley, 1992). Levee failure, and the concomitant flooding of the agricultural land, causes substantial landward movement of brackish water, threatening the quality of delta water.

The cited causes of land subsidence in the delta include oxidation of soil organic matter, mechanical compaction, wind erosion, anaerobic decomposition, and dissolution of soil organic matter (e.g., Weir, 1950; Prokopovitch, 1985). However, oxidation of soil organic matter is recognized internationally as the primary cause of long-term subsidence in organic soils (Armentano, 1980; Stephens and others, 1984). The objectives of the investigations

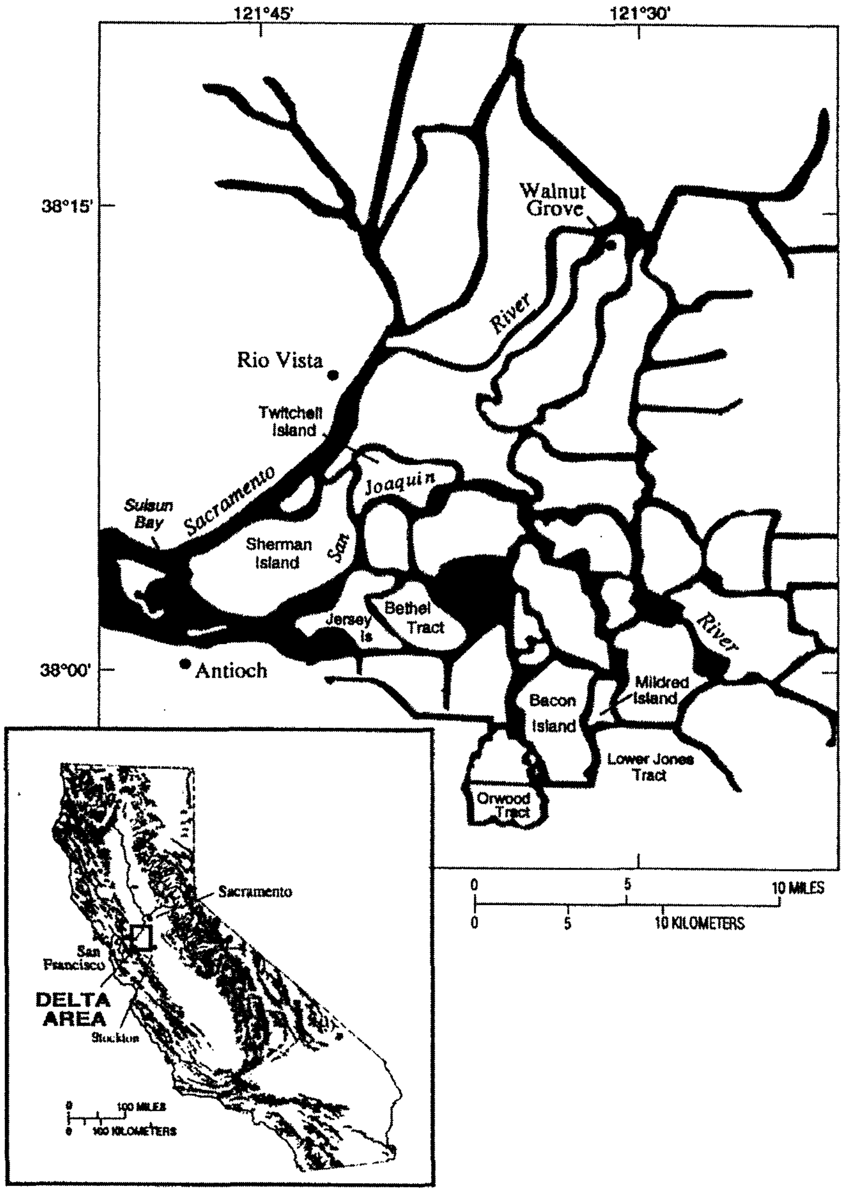

Figure 1. Location of the Sacramento–San Joaquin Delta.

described in this paper were to (1) identify the processes contributing to land subsidence in the organic soils of the Sacramento–San Joaquin Delta, (2) quantify these processes and the influence of physical and chemical factors affecting these processes, and (3) evaluate the effect of selected water-management strategies on land subsidence. These objectives were addressed by (1) evaluating historical subsidence rates and the factors affecting historical subsidence, (2) evaluating organic matter oxidation in relation to measured subsidence and chemical and physical factors in drained agricultural fields, and (3) evaluating land-surface elevation change and carbon flux in relation to water management practices on Twitchell Island in the western delta.

This paper summarizes the results of these investigations conducted from 1988 to 1995. The results presented here are both previously published and unpublished. The evaluation of land-surface elevation and organic matter oxidation in relation to water-management practices on Twitchell Island has not been reported elsewhere and is reported here in some detail. The evaluations of historical subsidence rates and organic matter oxidation in agricultural fields have been reported elsewhere (Rojstaczer and others, 1991; Rojstaczer and Deverel, 1993, 1995; Deverel and Rojstaczer, 1996) and are presented in less detail.

HISTORICAL SUBSIDENCE

Changes in historical subsidence rates were determined using data collected from 21 land surveys conducted between 1922 and 1981 by University of California researchers. The surveys followed a route known as the Weir transect through the central delta on Lower Jones tract, Bacon Island, and Mildred Island (fig. 1) (Weir, 1950; Broadbent, 1960). The 18 surveys for which closure error information is available show that in general, the surveys were conducted to the accuracy of an ordinary survey (Smirnoff, 1961). The average closure difference for the surveys was 0.07 m. Weir (1950) considered a closure error of 0.09 m acceptable because of the difficult leveling conditions. Assuming that this closure error is random and distributed equally across the 13 km of the transect, the leveling error is small relative to the rate of subsidence. The methodology and benchmarks used in these surveys are described in detail by Rojstaczer and others (1991).

The mean annual subsidence rates were calculated from the mean elevation histories for each island. The mean elevation was calculated for every repeat survey by removing elevation data that were collected on highly mineralized soil. The decreases in land-surface elevation over time were compared with two statistical regression models that predict linear and logarithmic decreases in elevation over time.

Spatial variability in historical land subsidence was evaluated by determining the decrease in land-surface elevation relative to powerpole foundations in the western delta. The foundations of electrical transmission towers are mounted on pilings driven to refusal and are assumed to be stable platforms relative to the surrounding soil. The cumulative subsidence that occurred near the tower foundations was determined by comparing the present-day land-surface elevations, as measured using a level positioned in fields adjacent to each of the four foundations, to the elevations when the towers were first constructed (Rojstaczer and others, 1991). Soil samples were collected adjacent to the tower foundations and analyzed for organic matter content to determine the extent that variability in soil organic matter accounted for the variability in subsidence.

ORGANIC MATTER OXIDATION AND SUBSIDENCE IN DRAINED AGRICULTURAL FIELDS

To evaluate the relation between organic matter oxidation and present-day subsidence, measurement sites on Orwood tract, Sherman Island, and Jersey Island (fig. 1) were established. The thickness of the organic soils, cropping, and water-management practices were different at each site. Changes in land-surface elevation were measured using continuous recording extensometers (Riley, 1986). Adjacent to the extensometers, CO_2 (carbon dioxide) flux from the soil surface was measured using closed chamber measurements. The outflow of dissolved organic carbon (DOC) to drain water was determined in drainage ditches near the extensometers. The time series of land-surface elevation change and CO_2 flux were examined as a function of soil temperature, soil moisture, and water-table elevation. Finally, subsidence estimated from CO_2 flux was compared with measured changes in land-surface elevation.

Field Site Descriptions

Sites on three drained agricultural islands (Jersey Island, Sherman Island, and Orwood tract, fig. 1) were selected to represent a range of environments and land-use practices anticipated to affect oxidation of soil organic matter and subsidence rates. All three islands are drained through a network of open ditches. Five locations were established on each of the three islands for monthly measurements of CO_2 flux, soil temperature, and soil moisture content.

At the Jersey Island site, about 3 m of organic soil overlies a chemically reduced, coarse-grained stratum. This site is in a 5.8-ha field that was planted with corn in 1986, but was not cultivated afterward. During the study, the primary vegetation was Bermuda grass (*Cynodon dactylon*). The water table is almost always within 1.5 m of land surface and was within 30 cm of land surface for several months during the year.

At the Orwood tract field site, 0.6 to 1.3 m of organic soil overlies a reduced organic clay stratum. The extensometer site is located on the edge of a 22.1-ha field that was planted with asparagus (*Asparagus officinalis*). The water table fluctuates, but generally was deeper than 1.0 m below land surface.

At the Sherman Island field site, 7.6 m of organic soils and sediment overlies a chemically reduced clay with lenses of organic material. The site is in a 26.1-ha field that was planted with wheat (*Triticum aestivum*) in 1990, which was harvested in July 1990. The field was fallowed and cultivated from July 1990 through May 1992. The water table was consistently deeper than 0.7 m below land surface.

Gaseous and Aqueous Carbon Flux Measurements

Measurements of CO_2 concentrations determined in a closed chamber during 20-min periods provided the data for calculating the gaseous CO_2 flux from the soil, similar to methods described by Rolston (1986). The chamber was a cylinder 92 cm in diameter and 23 cm high, constructed of 22-gauge sheet metal. A ring of angle iron was attached to the outside of the chamber, 5 cm from the open end, to ensure that the chamber was set at the same depth at each site. Samples for CO_2 analysis were taken from a sampling port in the center of the top of the chamber, which was sealed with a rubber septum. A 17.8 × 1.25-cm copper tube in the top of the chamber provided pressure equalization as with methods described by Hutchinson and Moiser (1981). To reduce wind infiltration through the soil (Matthias and others, 1980), the chamber was covered with a large tarp that was held down with lengths of chain. A large umbrella was used to shade the chamber and reduce radiant heating. Gas samples were drawn from the chamber and analyzed for CO_2 using a portable gas chromatograph equipped with a thermal conductivity detector. The detector's response was read as peak height and was compared to the response of known concentrations of CO_2 in calibration standard gases that were analyzed before each flux measurement.

The temperature of the chamber was measured with a thermocouple each time a sample was withdrawn for CO_2 analysis. These temperature measurements were used to make ideal gas law corrections for volume changes caused by temperature changes during the flux measurements. Temperature measurements made inside the chamber did not vary more than ±3°C during the flux measurements.

Water samples were collected for the determination of DOC and organic carbon fractionation in the drainage ditches adjacent to each field site. When there was flow into the ditches, the flow velocity was measured with an electromagnetic velocity meter placed in the outflow pipe that lead into a large drainage canal on Orwood tract and Jersey Island. The cross sectional area of flow was calculated from the internal geometry of the pipe and the measured height of flow in the pipe. The flow was calculated as the product of the velocity and the cross sectional area. At Jersey Island, we were unable to measure flow in the drainage ditch, and we estimated the volume of water leaving the field from changes in water levels. The samples for DOC were filtered through 0.45-µm silver membrane filters into a glass sample bottle and packed on ice until analysis. Concentrations of DOC were determined by methods described by Wershaw and others (1987).

EFFECTS OF WATER-MANAGEMENT PRACTICES ON TWITCHELL ISLAND

Because organic matter degradation rates under flooded conditions generally are slower than under nonflooded conditions, converting drained agricultural fields to wetlands that are flooded some part of the year could aid in subsidence mitigation. To evaluate this hypothesis, three wetland water-management strategies were evaluated for potential use in subsidence mitigation on three plots: a seasonal flooding, a seasonal flooding with irrigation, and a permanent flooding. The seasonally flooded plot was flooded from early fall through winter and drained during the spring and summer; the irrigated plot received two summer irrigations in addition to the fall and winter flooding; and the permanently flooded plot was flooded year round. The potential for subsidence mitigation of each water-management practice was evaluated by determining carbon mass balance for each plot. The carbon mass balance was determined by measuring the gaseous carbon flux from the plots and carbon accumulation in plant biomass.

Field Site Descriptions

Plots for evaluating different wetland water-management practices on subsidence and carbon flux were established on the southwestern edge of Twitchell Island (fig. 1). Three wooden enclosures were constructed, one on each plot. Each enclosure was equipped with an observation well for water-level measurements and a wooden walkway to minimize disturbance during flux measurements. Two sites within each plot were established as carbon-flux measuring sites. Two carbon-flux measurement sites were established at a fourth site that was not intentionally flooded, herein referred to as the drained site.

Gaseous Carbon Flux Measurements

The chamber and methods used to evaluate the gaseous carbon fluxes from the water-management plots on Twitchell Island were modified from those used for the evaluation of organic matter oxidation and subsidence in the drained agricultural fields to accommodate the flooded environment. The chambers were modified from those described by Delaune and others (1983) and Cicerone and others (1992). The chambers were constructed of a 30.5-cm-diameter stainless steel base with a 5-cm-high wedge welded around the outside, Plexiglas chamber flights, and a mylar balloon as the chamber cover. The stainless steel base was pressed into the soil to the base of the wedge and remained in place for the duration of the study. When the plots were not flooded, the wedge was filled with water during the flux measurements to provide a seal between the chamber base and the Plexiglas chamber flight. The chamber flights were stacked as necessary, and the chamber top was sealed using the mylar balloon, as described in Cicerone and others (1992). The design allowed the chamber height to be adjusted as vegetation grew. Gas samples were withdrawn from the chambers using syringes, and CO_2 and methane (CH_4) concentrations were quantified using field portable gas chromatographs. Carbon dioxide and CH_4 were detected with thermal conductivity and flame ionization detectors, respectively.

Measurement of Carbon Accumulation in Biomass on Twitchell Island

Plant biomass samples were collected from the plots in February and October 1993 and October 1994. Six samples were taken in randomly located 61 × 61-cm plots within each plot. All vegetation within these plots was removed at ground height, dried, and ground, and the carbon content measured with a carbon, hydrogen, and nitrogen analyzer. The plant biomass samples were reflective of growth from about February to October for both 1993 and 1994. The plots were first operated in February 1993 when vegetation was first beginning to grow. This vegetation began to die in October 1993 and began to grow again in February 1994.

SOIL MOISTURE, SOIL ORGANIC CONTENT, AND WATER-TABLE AND LAND-SURFACE ELEVATION MEASUREMENTS

The following methods were used during the evaluations of organic matter oxidation and subsidence in drained agricultural fields and the effects of water-management practices on Twitchell Island. At all sites, soil moisture content was determined with a neutron moisture probe that was calibrated in the field to volumetric water content (cm^3 H_2O/cm^3 soil) as described by Bell and McCulloch (1983). The percentage of organic matter in soil samples was determined by loss on ignition as described by Nelson and Sommers (1982). Water-table elevation was determined at each site with a vented Druck silicon strain bridge pressure transducer (300-mb range relative to atmospheric pressure) submerged in 2.5-m deep wells with slotted 5.1-cm-diameter casing. The transducers were connected to data loggers and sampled hourly.

The structure of the extensometers used for elevation measurements consisted of three 3.1-cm-diameter steel pipe piers inserted into 5.1-cm-diameter PVC cased holes. The three piers, forming a 2-m equilateral triangle, were driven to refusal into the underlying mineral soil. The three piers exposed above the land surface were cut so that their tops formed a horizontal plane, and angle iron was welded onto the pipe to form a triangular frame. The body of the displacement transducer was attached to the angle iron, and the rods were connected to the land surface by a 0.6-cm thick, 100-cm^2 aluminum plate that rested on the soil. Displacement transducers (linear variable differential transformer, 5.1-cm range) also were connected to the data loggers and measured the changes in land-surface elevation relative to the angle iron structure.

RESULTS AND DISCUSSION

Historical Subsidence

The data from the Weir transect surveys provide a unique record of subsidence history on three islands in the delta. The mean annual subsidence rates were calculated from the mean elevation histories for each island. Estimates of time averaged subsidence rates were 5.1, 7.6, and 7.6 cm/yr on Lower Jones tract, Mildred Island, and Bacon Island, respectively, between 1925 and 1981 (Rojstaczer and others, 1991). However, evaluation of historical subsidence data indicates that subsidence is slowing, and a temporally and spatially averaged rate may overestimate the current rate of subsidence.

The temporal changes in spatially averaged land-surface elevation measured along the Weir transect are shown for the three islands in figure 2. Regression analysis using linear and logarithmic models were used to evaluate these temporal changes. For the data for all three islands, the logarithmic model explains a greater or similar amount of the variance compared to the linear model. Comparing the residuals of the predicted elevation losses for the two models with the actual elevation losses indicates that the logarithmic model is the appropriate model for all three data sets. For the logarithmic model, the residual values are normally distributed around zero over the range of the data. In contrast, the residuals of the linear model are negatively skewed and not normally distributed. The better fit of the

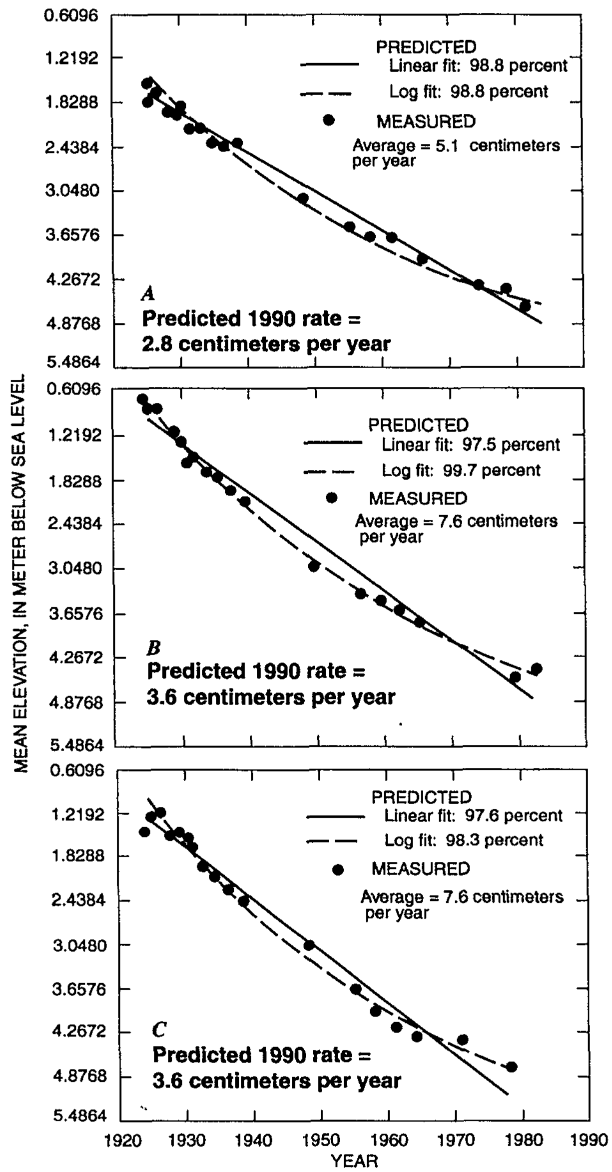

Figure 2. Average changes in land-surface elevation measured along the Weir transect for (*A*) Lower Jones tract, (*B*) Mildred Island, and (*C*) Bacon Island.

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logarithmic model indicates that subsidence rates are slowing over time. Using the logarithmic model, Rojstaczer and Deverel (1993) estimated the rate of subsidence in 1990 to be 3.6 cm/yr for Bacon and Mildred Islands and 2.8 cm/yr for Lower Jones tract.

Subsidence histories were constructed for each of the islands along the transect by drawing contours of equal cumulative elevation loss for the years for which survey data were available (Rojstaczer and others, 1991) The types of crops growing along each leg of the transect were compared with the spatial and temporal changes in elevation losses to assess the effects of land use on subsidence. This analysis indicated that spatially variable subsidence rates were relatively unaffected by land-use patterns on the three islands. The one notable exception occurred between 1938 and 1948 when there seemed to be an increase in the rate of subsidence. Although data about land use were not available for this time period, Thompson (1957) observed that sugar beets and potatoes were the predominant crops grown in the delta during World War II due to the war-time demand for these products. Because sugar beets and potatoes benefited from the ash remaining after burning, controlled burning that results in peat combustion was practiced throughout the war years (Thompson, 1957) and may be the reason for the increased subsidence rates during this period.

Spatial variability in historical land subsidence also was assessed from the decrease in land-surface elevation in relation to power-pole foundations (Rojstaczer and others, 1991; Rojstaczer and Deverel, 1995). Subsidence at the electrical transmission tower foundations on Sherman Island was greatest where the organic matter content of the adjacent soil was greatest (fig. 3). The foundations on Sherman Island were increasingly exposed toward the island center, showing a maximum elevation loss of about 2.4 m (3.1 cm/yr) near the center of the island from 1910 to 1988. The lowest rate of subsidence, 1.3 cm/yr, was measured near the edge of the island. The temporally and spatially averaged subsidence rate for Sherman Island was 2.5 cm/yr (Rojstaczer and others, 1991) from 1910 to 1988.

The larger, spatially averaged subsidence rates on the central delta islands (Lower Jones tract, Mildred and Bacon islands) are due to the higher organic matter content of the island soils. Historically, the western delta received more sediment deposited by the Sacramento and San Joaquin Rivers than the central delta, causing the western delta soils to have a higher mineral content relative to the central delta soils. Similarly, the margins of the delta islands have been more influenced by fluvial sedimentation than have the central parts of the islands.

Organic Matter Oxidation and Subsidence Rates in Drained Agricultural Fields

The relation between organic matter oxidation and the present-day subsidence rates in the Sacramento–San Joaquin Delta was evaluated using CO_2 flux as the indicator of organic matter oxidation. The average CO_2 flux measured at the chamber sites in fields on Jersey Island, Orwood tract, and Sherman Island are shown in figure 4. The CO_2 flux at all three field sites generally increased to maximum values during the spring and summer and decreased to minimum values in the

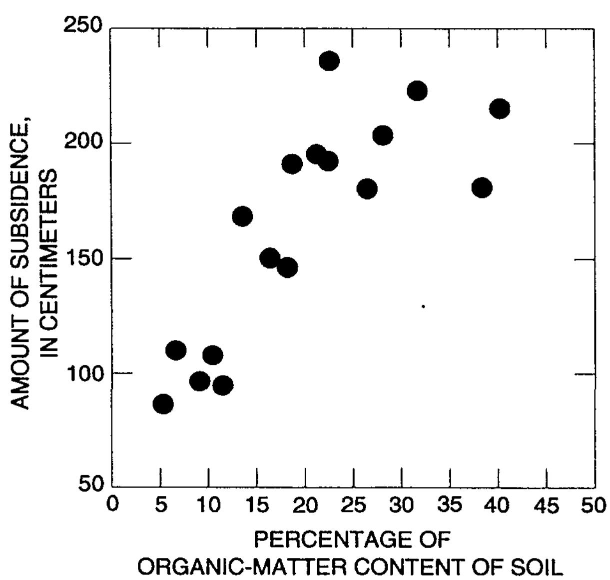

Figure 3. Relation of land-surface elevation and soil organic matter content for Sherman Island.

autumn and winter. Spatial and temporal variability of CO_2 flux was related to soil temperature. The logarithm of CO_2 flux and soil temperature at a depth of 30 cm were significantly ($\alpha = 0.001$) correlated for all measurements made on Jersey Island ($r^2 = 0.47$), Orwood tract ($r^2 = 0.48$), and Sherman Island ($r^2 = 0.32$).

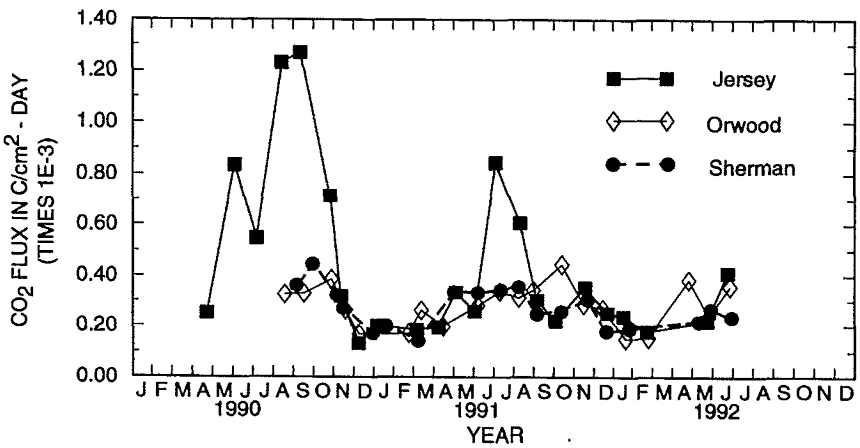

Figure 4. CO_2 flux measured on Jersey Island, Orwood tract, and Sherman Island, March 1990 to May 1992. The points represent the arithmetic average of measurements at five sites on each island or tract.

On Sherman Island, the relation between soil temperature and CO_2 flux is somewhat similar to the relations observed on Jersey Island and Orwood tract, but the correlation of the logarithm of CO_2 flux with soil temperature explains only 32 percent of the variance. The CO_2 flux on Sherman Island seems to be affected by drying and cracking of the soil caused by a lack of irrigation. Large CO_2 flux values were measured during the summer of 1991 and the winter of 1992 at two of the five measurement points. Measurements were taken when cracks were visible at the chamber sites. The cracks extended as much as 1 m in depth where CO_2 concentrations in the soil gas can be as high as 10 percent. Carbon dioxide fluxes from these cracks probably are much larger than fluxes measured where there are no cracks because the cracks allow degassing of areas of high CO_2. Subsurface cracks that are not visible at the surface also form in delta organic soils as they desiccate (Hansen and Carlton, 1985). The surface and subsurface cracks may cause CO_2 fluxes to vary more independently of soil temperature than at the other sites.

Soil moisture also influenced the CO_2 flux-temperature relations. In general, CO_2 fluxes that were above the mean were measured when the soil moisture was between 0.30 and 0.50 cm^3 H_2O/cm^3 soil, and the soil temperature was between 12 and 25°C. Soil temperatures generally are within this optimum range from May through October. Soil moisture conditions vary substantially depending on irrigation and rainfall, but moisture conditions generally are in this range during the spring and summer when the maximum fluxes were measured. A combination of saturated soil conditions and low soil temperatures caused CO_2 fluxes to remain low during the late fall, winter, and early spring. Higher CO_2 fluxes resulted from low soil moisture content and higher temperatures during the late spring, summer, and early fall.

Changes in land-surface elevation on each of the three islands are related to changes in water levels and to CO_2 losses. As an example, figure 5 shows changes in land-surface elevation and water levels for the Jersey Island extensometer site. The land-surface elevation changes with fluctuating water levels. This is probably the buoyancy effect because the bulk density of the organic soils are less than 1 g/cm^3. However, there is a permanent component of the land-surface elevation change demonstrated by a change in land-surface elevation between points of equal hydraulic head. This net subsidence was 1.01 cm from early April 1990 to late February 1992 when hydraulic head values were about equal. This corresponds to a net subsidence rate of about 0.55 cm/yr. Most of the net subsidence

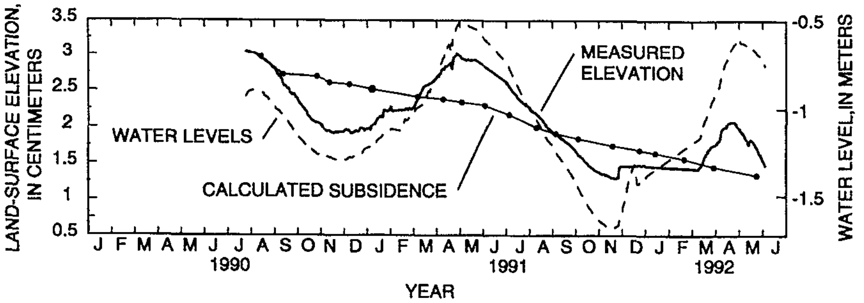

Figure 5. Measured changes in land-surface elevation and water levels and estimated elevation changes based on CO_2 flux at the extensometer sites on Jersey Island.

Table 1. Measured Annual Subsidence Rates and Subsidence Rates Calculated from CO_2 Flux on Jersey and Sherman Islands and Orwood Tract

Island	Measured Rate (cm/yr)	Calculated Rate (cm/yr)
Jersey	0.6	0.92
Sherman	0.49	0.32
Orwood Tract	0.8	0.62

appears to be due to the oxidation of organic matter, as determined from CO_2 flux.

The proportion of measured CO_2 flux resulting from organic matter oxidation at the extensometer site was estimated using the carbon isotope data described by Rojstaczer and Deverel (1993). The carbon-14 and carbon-13 isotopic composition was determined for gas samples collected from chambers to determine the portion of the CO_2 that originated from plant root respiration and organic matter oxidation. Distinguishing between organic matter and root derived CO_2 is necessary to calculate the subsidence rate based on the CO_2 flux because only the organic matter derived flux relates to subsidence. Organic matter oxidation during February through November, when vegetation was actively growing, was about 50 percent of the measured CO_2 flux. The measured CO_2 flux was determined to be entirely the result of organic matter oxidation in December and January.

Subsidence calculated from CO_2 loss was calculated and is plotted in figure 5. The CO_2 flux was converted to an elevation loss using the average soil bulk density of samples collected near the extensometer (0.85 g soil/cm^3 soil) and soil organic matter content (24.4 percent). The carbon content of the organic matter was assumed to be 50 percent (Broadbent, 1960). Subsidence calculated from CO2 fluxes agrees well with the net subsidence measured by the extensometer (table 1).

Regression analysis of the relation of land-surface elevation changes, land-surface elevation changes predicted from CO_2 flux, and water levels reveals that not all variance in land- surface elevations can be explained by CO_2 flux. First, subsidence not related to water-level changes was calculated by regressing land-surface elevation changes on water levels. Next, residuals from this analysis were regressed against the calculated subsidence. This relation explained about 76 percent of the variance for the Jersey Island data. About 24 percent of the variance in land-surface elevation changes is not accounted for by the carbon-flux model. For the Orwood tract and Sherman Island data, 60 and 63 percent, respectively, of the variances were explained.

Uncertainty and error in the carbon-flux-based estimates of subsidence include the portion of CO_2 flux derived from organic matter oxidation and plant-root respiration and the temporal variability in CO_2 fluxes. Isotope analysis discussed by Rojstaczer and Deverel (1993) provided little information about the temporal variability in the relative proportion of plant-root respiration and organic matter oxidation in the CO_2 flux. The diurnal fluctuation in CO_2 fluxes was accounted for in the subsidence estimate by assuming that the CO_2 fluxes decreased by 50 percent during the night and early morning. This assumption was based on one set of hourly diurnal flux measurements at one site on Jersey Island, and the diurnal changes in CO_2 fluxes probably varied seasonally and by site.

Estimates of subsidence due to aqueous organic carbon loss were based on the hypothesis that carbon in the form of DOC, mobilized in the saturated and unsaturated zone, may cause a decrease in land-surface elevation. Subsidence estimates shown and discussed by Deverel and Rojstaczer (1996) were small (less than 1 percent) relative to the subsidence rates measured by the extensometers.

Water-Management Practices on Twitchell Island

The results of semimonthly gaseous carbon-flux measurements made in the three plots and on the two drained sites are shown in figure 6. Carbon dioxide was the primary gaseous species emitted from the irrigated, seasonal, and drained plots with fluxes ranging from below detection to 1.7 $\times 10^{-3}$ g carbon/cm^2/day. Carbon dioxide fluxes were not detected when the sites were flooded, and sporadic CH_4 fluxes were measured at these sites.

Methane was the primary gaseous carbon species determined in gas flux measurements on the permanently flooded plot. Average carbon fluxes in the form of CH_4 from the flooded plot were about five times lower than the average carbon fluxes in the form of CO_2 from the other two plots. Initially, there was no CO_2 flux in the flooded plot. However, in the spring of 1995, CO_2 flux was determined in the flooded plot and was assumed to be due to plant root respiration. When the plot was first flooded in 1993, there was no vegetation growing, but there was extensive vegetative growth by the spring of 1995.

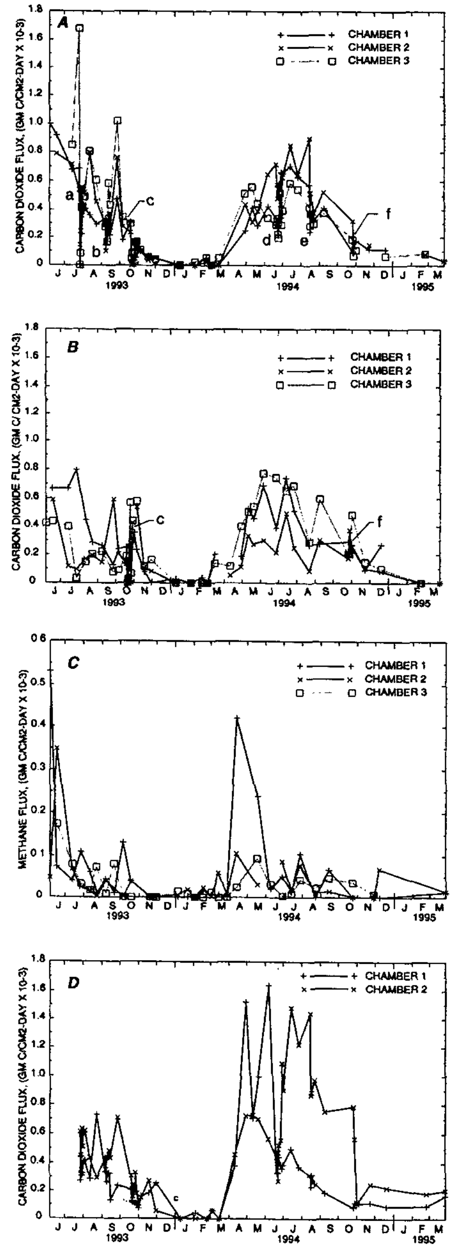

Figure 6. Gaseous carbon flux from plots on Twitchell Island. (*A*) CO_2 flux in the irrigated plot; points a, b, d, e are the 1993 and 1994 irrigation and points c and f are the winter flooding; (*B*) CO_2 flux for the seasonally flooded plot, points c and f are winter flooding; (*C*) CH_4 flux for the permanently flooded plot; and (*D*) CO_2 at the drained site; point c is unintentional flooding.

The effects of irrigation on carbon flux in the irrigated plot are shown in figure 6*A*. The labels a through f on the figure indicate irrigation and flooding dates. Fluxes dropped about ten-fold 24 hr after the July 26, 1993, irrigation (a on fig. 6*A*) and about twofold 24 hr after the September 7, 1993, June 21, 1994, and August 14, 1994, irrigations (b, d, and e, fig. 6*A*). The CO_2 flux returned to pre-irrigation levels within 72 hr, and a peak in CO_2 flux was measured approximately 2 weeks after irrigation.

Irrigation increased the soil moisture content measured at 0.15 m in the irrigated plot from a pre-irrigation value of about 25 percent to about 55 percent (by volume) after irrigation. The moisture content returned to the pre-irrigation value after about 1 month. The highest flux values for both the seasonally flooded plot and the drained sites occurred at moisture contents between 20 and 30 percent.

Winter flooding of the irrigated and seasonal plots occurred on October 20, 1994 (c on fig. 6*A*, *B*). The CO_2 flux decreased 24 hr after flooding and increased a week after flooding and then decreased to very low values in November through February (fig. 6*B*). No CH_4 flux was detected in the seasonal or irrigated plots, or at the drained sites throughout the flooded period. There was no detectable carbon flux during the winter in the permanently flooded plot.

Plant biomass samples were collected in the three plots immediately prior to flooding of the irrigated and seasonal plots in the late fall. The carbon content of the plant samples was representative of carbon accumulation on the plot during 1993 and 1994 and is considered to be the average carbon input. The carbon content of the biomass samples from the plots ranged from 0.061 g carbon/cm^2 for the seasonally flooded plot in 1993 to 0.16 g carbon/cm^2 for the permanently flooded plot in 1994 (table 2).

Carbon input in the irrigated and seasonal plots was similar for the second year of growth. Carbon values for the biomass collected in the second year for the flooded plot were about double the values for the previous year, which is probably the result of the slow breakdown of carbon under flooded conditions. We observed mats of vegetation 15 and 30 cm deep overlying the peat soil in the flooded plot in 1993 and 1994, respectively. On the basis of the assumptions that the carbon in the plant biomass samples represented the primary carbon input and that the CO_2 or CH_4 fluxes were the primary carbon output from the plot, we calculated the carbon mass balance for each plot. There was a net carbon gain in the permanently flooded plot and net carbon losses in the irrigated and seasonal plots (table 2).

SUMMARY AND CONCLUSIONS

In the Sacramento–San Joaquin Delta, historical, time-averaged subsidence rates range from 1.3 to 7.6 cm/yr. Subsidence rates in the western delta are generally lower relative to the central delta because soil organic matter contents are generally lower. Analysis of historic leveling data indicates subsidence rates are slowing over time. Spatially variable subsidence rates were correlated with soil organic matter content on Sherman Island. Varying agricultural land-use practices do not substantially affect subsidence rates on three central delta islands.

Carbon dioxide fluxes in organic soils in three drained agricultural fields in the western delta vary seasonally and are affected primarily by soil temperature and secondarily by soil moisture and soil organic matter content. Subsidence rates measured from 1990 to 1992

Table 2. Carbon Mass Balance for the Three Plots on Twitchell Island

Plot	Average Carbon Flux (C/cm^2/yr)	Average Input (C/cm^2/yr)	Difference (Input – Flux) (C/cm^2/yr)
Irrigated			
1993	0.12	0.07	–0.05
1994	0.12	0.07	–0.05
Seasonal			
1993	0.09	0.06	–0.03
1994	0.09	0.07	–0.02
Flooded			
1993	0.02	0.07	0.05
1994	0.02	0.16	0.14

ranged from 0.68 cm/yr on Jersey Island, to 1.06 cm/yr on Orwood tract, to 0.46 cm/yr on Sherman Island.

For all three drained agricultural sites, subsidence calculated from gaseous CO_2 losses due to organic matter oxidation agreed reasonably well with measured permanent subsidence. Carbon losses in the form of CO_2 explain about 60 to 76 percent of the variance in changes in land-surface elevations when the effects of water-level fluctuations are removed. Estimates of DOC flux for all three sites were small relative to gaseous CO_2 losses and represent less than 1 percent of the measured subsidence.

Carbon flux measured at three plots indicates that permanent flooding of organic soils can reverse the effects of subsidence. Carbon balances determined from measurements of gaseous carbon losses and carbon gains in the form of biomass accumulation were negative for seasonally flooded and irrigated plots and positive for the permanently flooded plots. The positive carbon balance for the permanently flooded plot indicates that flooding causes carbon to accumulate and may lead to accretion of the land surface.

The primary gaseous forms of the carbon fluxes were CO_2 for the seasonally flooded and irrigated plots and CH_4 for the permanently flooded plot. Carbon fluxes from the permanently flooded plot were about an order of magnitude lower than the carbon fluxes from the seasonally flooded and irrigated plots, indicating that the rate of organic matter oxidation decreased substantially under flooded conditions. Maximum CO_2 fluxes were measured during the summer when soil moisture content was between 20 and 30 percent.

The results presented here have implications for management strategies associated with drainage of organic soils in this and other regions. Present-day rates of elevation loss described here are lower than rates reported for this region in the past and are consistent with the inferred slowing of subsidence rates over the last 80 yr. The results presented here indicate that conversion of delta agricultural land to wetlands could reduce oxidation and mitigate subsidence.

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